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Silicon Integrated InGaAs/InAlAs/AlAs HBV Frequency Tripler

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***Abstract*— We present an integrated heterostructure barrier varactor (HBV) frequency tripler on silicon substrate. The InGaAs/ InAlAs/ AlAs material structure was transferred onto the silicon wafer using low temperature plasma assisted bonding. The presented multiplier operates in the W-band (90-110 GHz). The module delivers 22.6 dBm, with a conversion loss of 6 dB, and 9 % 3-dB bandwidth.**

***Index Terms*— Frequency multipliers, heterostructure barrier varactors, heterogeneous integration, integrated circuits, millimeter-wave diodes, silicon, wafer bonding, III-V semiconductors.**

I. Introduction

The III-V compound semiconductors are broadly used in active devices operating at mm-wave and THz frequencies [1]- [2]. III-Vs offer high electron mobility, high bandgap and the epitaxial growth allows for fabrication of complex layer structures. However, at THz frequencies, monolithic integrated circuits require ultra thin substrates and on chip antenna probes for signal coupling, which occupy large wafer area. This is not easily made on materials like InP or GaAs which are fragile, expensive and are limited to small wafer sizes.

Silicon is a mechanically robust material. It is cheap, supports large wafer sizes (>8 "), and is suitable for micromachining of complex 3 D structures [3]. In addition, it has two times higher thermal conductivity than InP or GaAs, which is an advantage for power dissipating devices. By heterogeneous integration of III-Vs on Si high frequency active devices on membranes, integrated in waveguides will be possible [4]- [5]. This will provide an additional degree of freedom in the circuit design and fabrication.

Both direct epitaxial growth and epitaxial transfer methods have been used for the heterogeneous integration of III-Vs on Si [6]. For microwave applications a GaAs MESFET [7], an InGaP/ GaAs [8], InGaAs/ InP [9] HBTs, and an AlGaN/ GaN HEMT [10] on Si have been demonstrated. Epitaxial transfer methods for THz frequency multipliers onto quartz [11]- [12] and AlN have been presented. However, direct integration of these integrated circuits onto Si, and the studies of the thermal properties and losses have not been shown.

In this letter, an integrated InGaAs/ InAlAs/ AlAs HBV frequency tripler on silicon substrate is presented. Due to 55 % thermal expansion coefficient mismatch between InP and Si a low temperature plasma assisted bonding was utilized [13]. The performance of the reported device is comparable with the state-of-the-art devices grown and processed directly on the lattice matched InP substrate [14]- [15]. This motivates further research, and development of applications operating at THz frequencies utilizing heterogeneous integrated III-Vs on silicon.

II. Design and Fabrication

A. HBV Devices

The HBV is a semiconductor device, which under an applied voltage exhibits a nonlinear and symmetric capacitance [16]. The capacitance modulation is possible by combination of low/ high/ low bandgap material Fig.1. The barrier thickness is optimized for minimum leakage current and maximum breakdown voltage [17]. The device area and the number of barriers are designed to handle ca 1W of the input power [18]. The HBV material structure was grown on 3 " InP substrate by molecular beam epitaxy. The HBV material was then transferred onto high resistivity silicon (>10 kΩ cm) using LT plasma assisted wafer bonding [19]. In Fig. 2, a TEM image of the transferred material and the amorphous oxide layer at the bonded interface are shown.

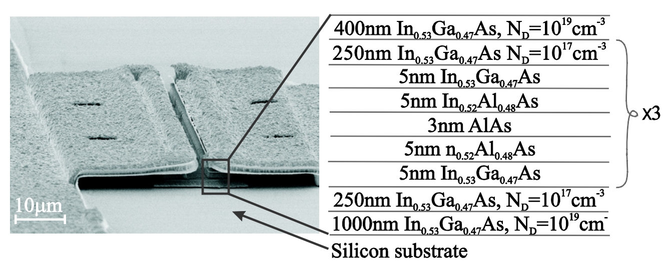

Fig.1. *Left*: SEM image of an integrated HBV diode with total 6 barriers, on the silicon substrate with the air bridge connections to the embedding circuit.
Right: depicted epitaxial layers of the HBV device. The mesa contact area is $7 \times 100\ \mu m^2$.

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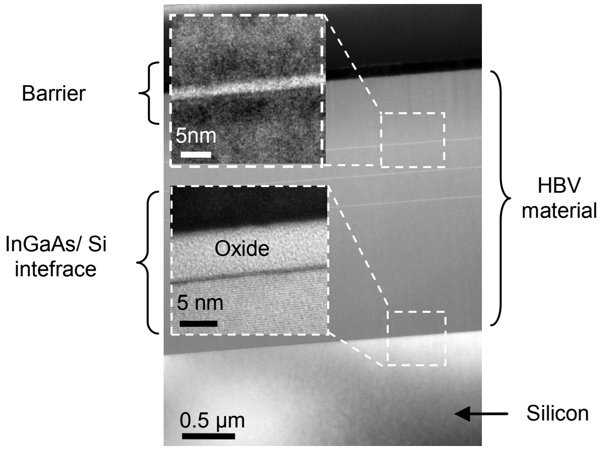

Fig. 2. TEM image presenting the III-V HBV on silicon, and the InGaAs-Si interface, with 5 nm thick oxide layer.

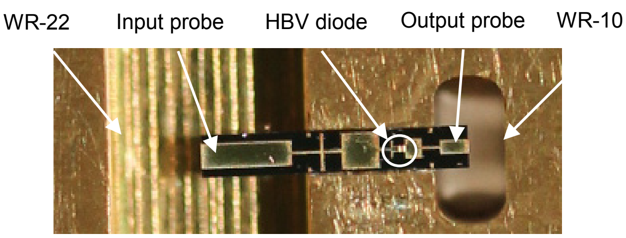

Fig. 3. Image of a silicon integrated HBV frequency tripler assambled in the waveguide channel. The chip dimensions are: 4.7 mm × 0.8 mm× 0.08mm (length× width× thickness).

Subsequently, the wafers were diced into 20×20 mm^2 chips, cleaned, and the integrated diodes and circuits were fabricated. This process consists of standard III-Vs fabrication steps. In addition, a 100 nm thick SiO_2 layer was sputtered on the silicon surface. The SiO_2 passivation had no influence on the circuits RF performance, but reduced the substrate DC conductance, allowing for accurate I-V characterization of the active devices.

B. Circuit

The tripler circuit design is described in [15], [20]. An image of the silicon integrated frequency tripler assembled in the waveguide channel is shown in Fig. 3. The input signal is coupled to the circuit with a waveguide probe. The matching is realized in microstrip technology. The output waveguide will effectively block the fundamental harmonic (ω_0). The generated signal at 3 ω_0, is coupled to the output waveguide (WR- 10) with a waveguide probe.

III. Results

The input signal was generated with an Agilent E8257D signal generator. This signal was amplified with a Spacek Labs Ka-band power amplifier. A 10 dB directional coupler and an Agilent E4418B power sensor were used for accurate control of the available pump power. The output power at the third harmonic was measured with an Erickson PM4 power meter. The characterization was performed for an input frequency sweep from 30 – 34 GHz with a 0.2 GHz step. The input power drive level was in the 20 − 29 dBm range.

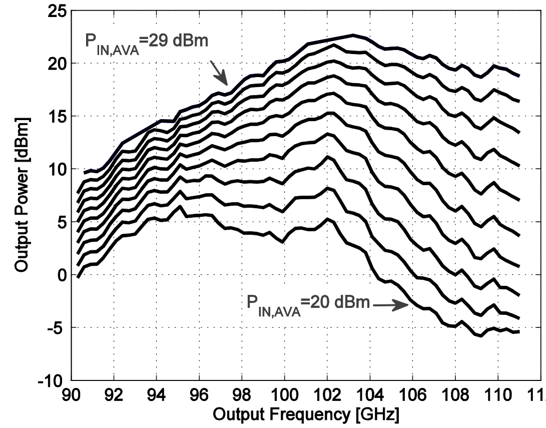

Fig. 4. Measured output power versus output frequency as a function of the available input power from 20 − 29 dBm in steps of 1 dBm.

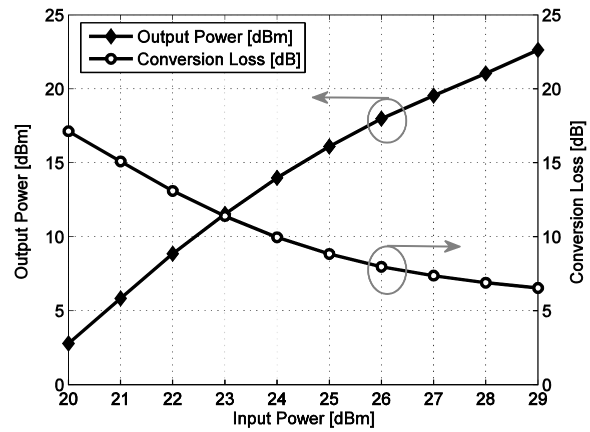

Fig. 5. Output power and conversion loss as a function of input power at 103 GHz output frequency.

The RF performance of the demonstrated × 3 frequency multiplier is shown in Fig. 4. The maximum output power for 29 dBm of the input power measured at 103 GHz was 22.6 dBm (184 mW). The 3-dB bandwidth for the presented device was approximately 9 %. In Fig. 5. the output power and conversion loss collected at the center frequency are presented. The conversion loss for this device is about 6 dB, and corresponds to 23 % efficiency.

Due to the limited saturated output power of the power amplifier (29 dBm), the tripler circuit could not be driven into saturation and therefore the maximum output power and efficiency were not reached.

IV. Conclusion

We have demonstrated a silicon integrated HBV frequency tripler. The performance of the presented device is comparable with the state-of-the-art hybrid and monolithically integrated InP-based frequency tripler devices [15]. The InGaAs/ InAlAs/ AlAs material structure was transferred onto silicon using LT plasma assisted bonding. By use of alloyed ohmic contact is a reason improved RF performance in comparison with the devices reported in [21].

The presented results motivate further research and development of III-V HBV devices integrated on silicon for THz frequencies. Silicon micromachining can be utilized to form membranes, waveguides, and antennas for more advanced integration schemes.

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